Single transverse spin asymmetry (SSA) of W/Z bosons

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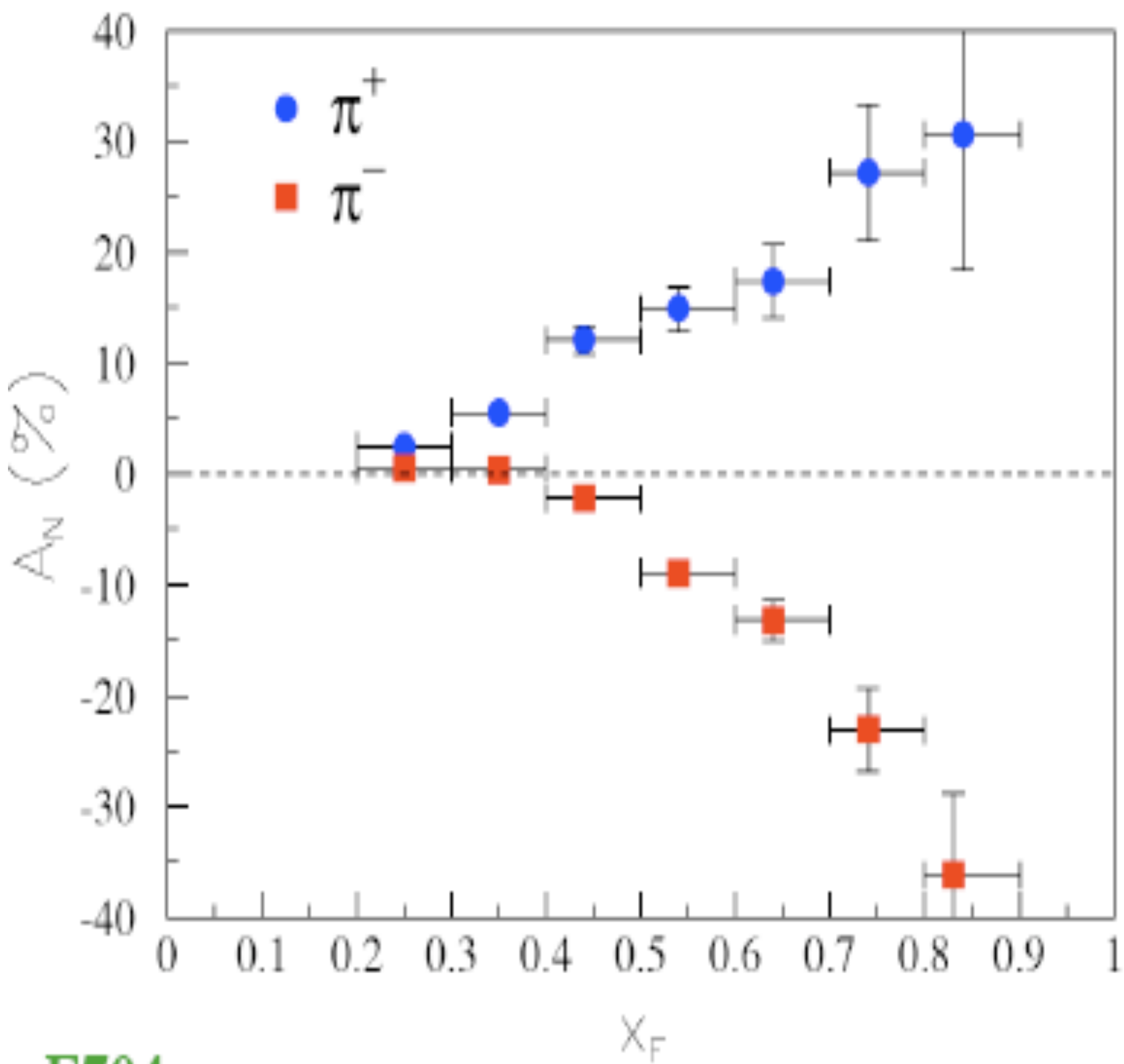
based on work with J. W. Qiu

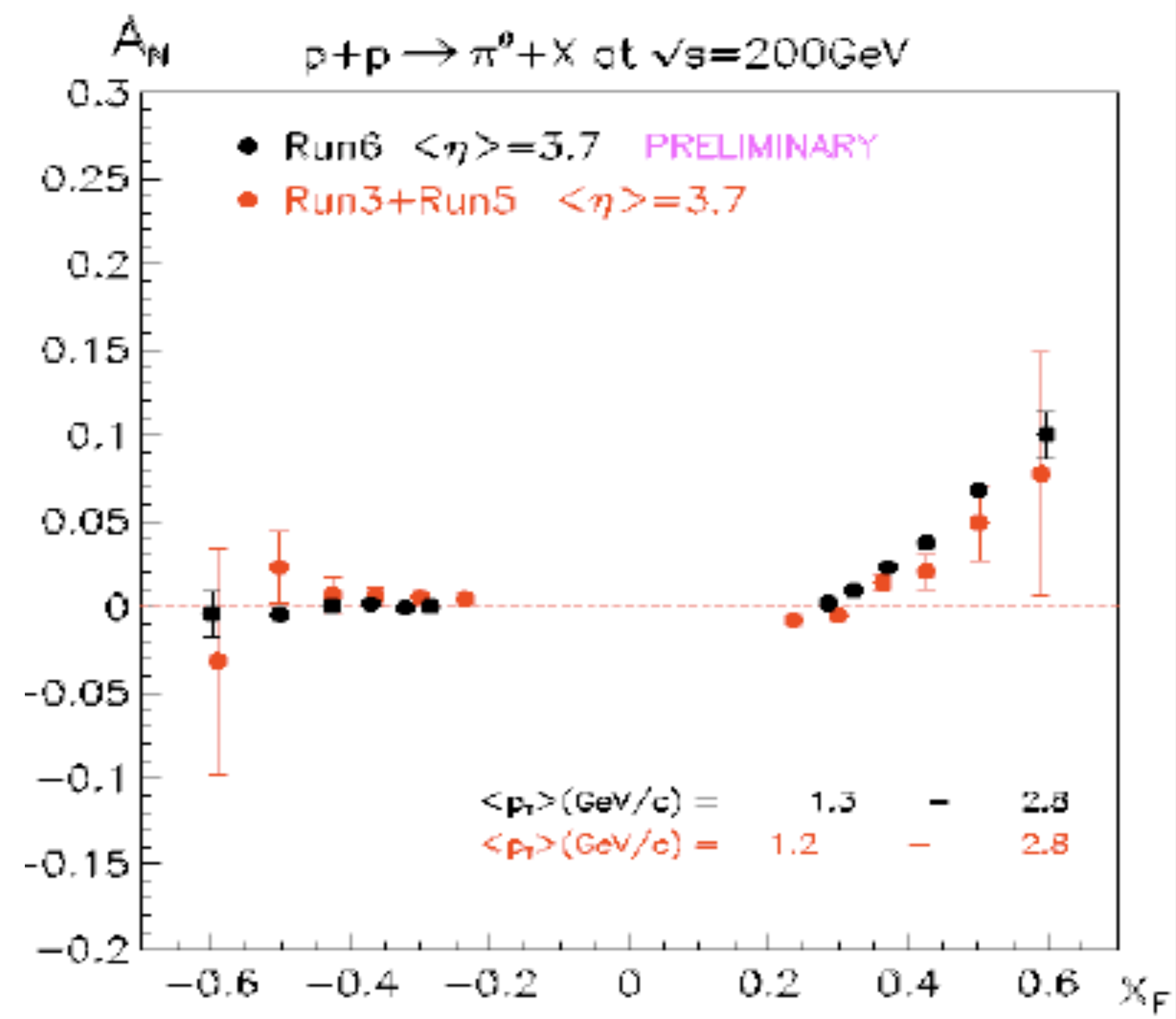
Experiment: Single Spin Asymmetries

- Fermilab E704, STAR, PHENIX, BRAHMS, COMPASS, HERMES, JLAB:

$$p^{\uparrow}p \rightarrow \pi X$$



E704

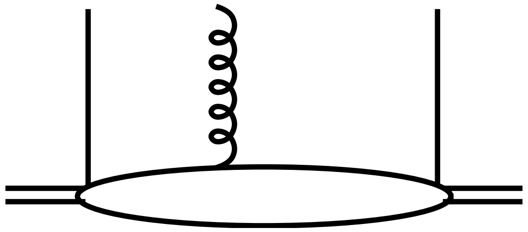


STAR (BRAHMS, too)

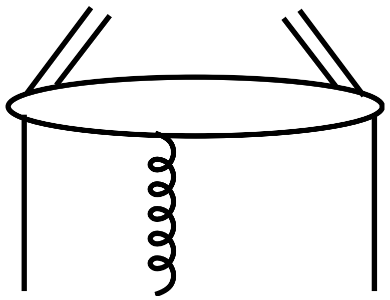
SSAs are observed in various experiments at different √s

Two mechanisms to generate SSA in QCD

- SSA is related to parton's transverse motion
- Collinear factorization approach:
  - Twist-3 three-parton correlation functions: Qiu-Sterman matrix element, ...
  - Twist-3 three-parton fragmentation functions:



Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98, ...



Koike, 02, Zhou, Yuan, 09

- TMD approach: Transverse Momentum Dependent distributions probe the parton's intrinsic transverse momentum
  - Sivers function: in Parton Distribution Function (PDF)

    Sivers 90

  - Collins function: in Fragmentation Function (FF)

    Collins 93

Relation between twist-3 and TMD approaches

- They apply in different kinematic domain:
  - TMD approach: need TMD factorization, applies for the process with two observed momentum scales: DY at small q_T

$$Q_1 \gg Q_2 \begin{cases} Q_1 & \text{necessary for pQCD factorization to have a chance} \\ Q_2 & \text{sensitive to parton's transverse momentum} \end{cases}$$

  - Collinear factorization approach: more relevant for single scale hard process: inclusive pion production at pp collision
- They generate same results in the overlap region when they both apply:
  - Twist-3 three-parton correlation in distribution ⟷ Sivers function

    Ji, Qiu, Vogelsang, Yuan, 06, ...
  - Twist-3 three-parton correlation in fragmentation ⟷ Collins function

    Zhou, Yuan, 09

Major difference in these two approaches

- Collinear factorization approach:
  - All the twist-3 correlation functions (both in distribution and fragmentation side) are universal
- However, the TMD function in TMD approach MIGHT not be universal
  - Sivers function is NOT universal

    Collins 02, Boer, Mulders, Pijlman, 03, Collins, Metz, 04, Kang, Qiu, 09, ...
  - Collins function is universal

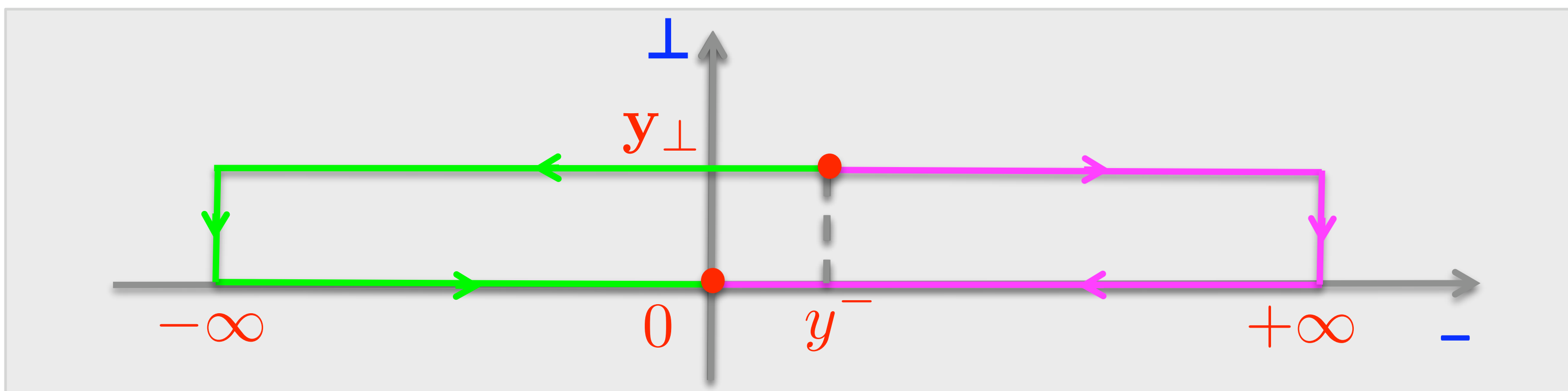
    Metz 02, Collins, Metz, 04, Yuan, 08, Gamberg, Mukerjee, Mulders, 08, Meissner, Metz, 08, Zhou, Yuan, 09, ...

Non-universality of the Sivers function

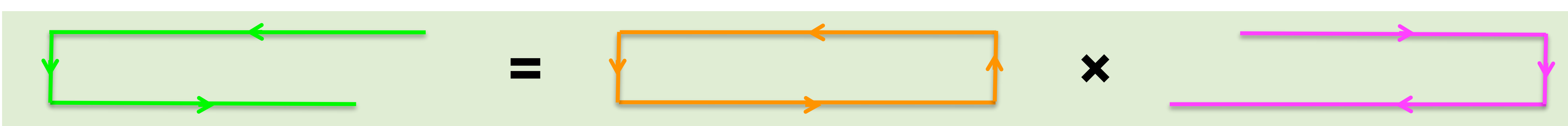
- Different gauge link for gauge-invariant TMD distribution in SIDIS and DY

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3}\, e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\, \boxed{\text{Gauge link}}\, \frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

  - SIDIS: $\Phi_n^\dagger(\{+\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(+\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{+\infty,y^-\},\mathbf{y}_\perp)$
  - DY: $\Phi_n^\dagger(\{-\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(-\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{-\infty,y^-\},\mathbf{y}_\perp)$



Wilson Loop ~ $\exp\left[-ig\int_\Sigma d\sigma^{\mu\nu}F_{\mu\nu}\right]$ Area is NOT zero



- For a fixed spin state:

$$f_{q/h^\uparrow}^{\text{SIDIS}}(x,\mathbf{k}_\perp,\vec{S}) \neq f_{q/h^\uparrow}^{\text{DY}}(x,\mathbf{k}_\perp,\vec{S})$$

Time-reversal modified universality of the Sivers function

- Relation between Sivers functions in SIDIS and DY
  - From P and T invariance:

$$f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x, \mathbf{k}_\perp, \vec{S}) = f_{q/h^\uparrow}^{\mathrm{DY}}(x, \mathbf{k}_\perp, -\vec{S})$$

    - **Spin-averaged parton distribution function is universal**

  - From definition:

$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/h^\uparrow}(x, k_\perp)\, \vec{S}\cdot\hat{p}\times\hat{\mathbf{k}}_\perp$$

  - One can derive:

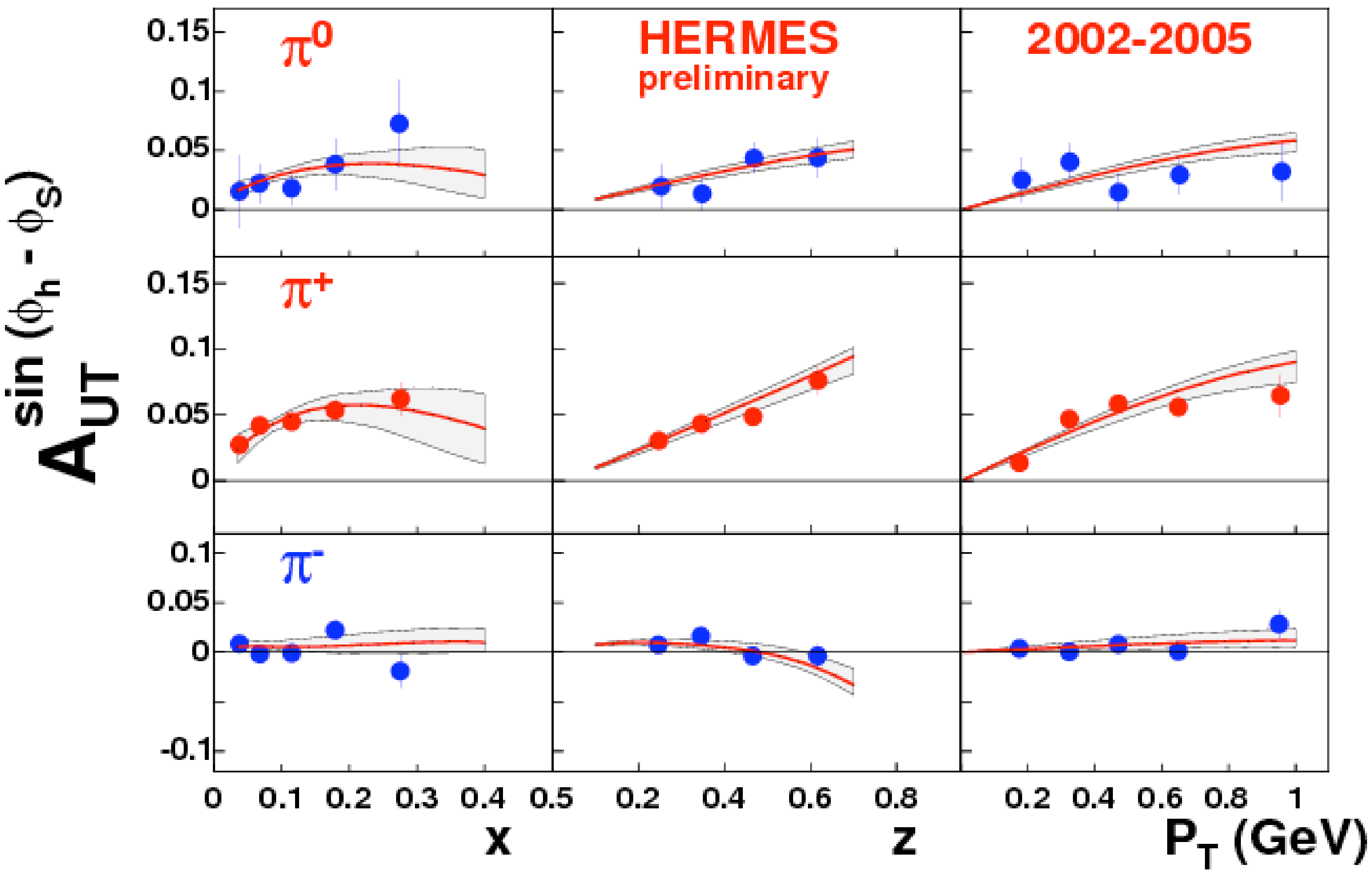
$$\Delta^N f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\mathrm{DY}}(x, k_\perp)$$

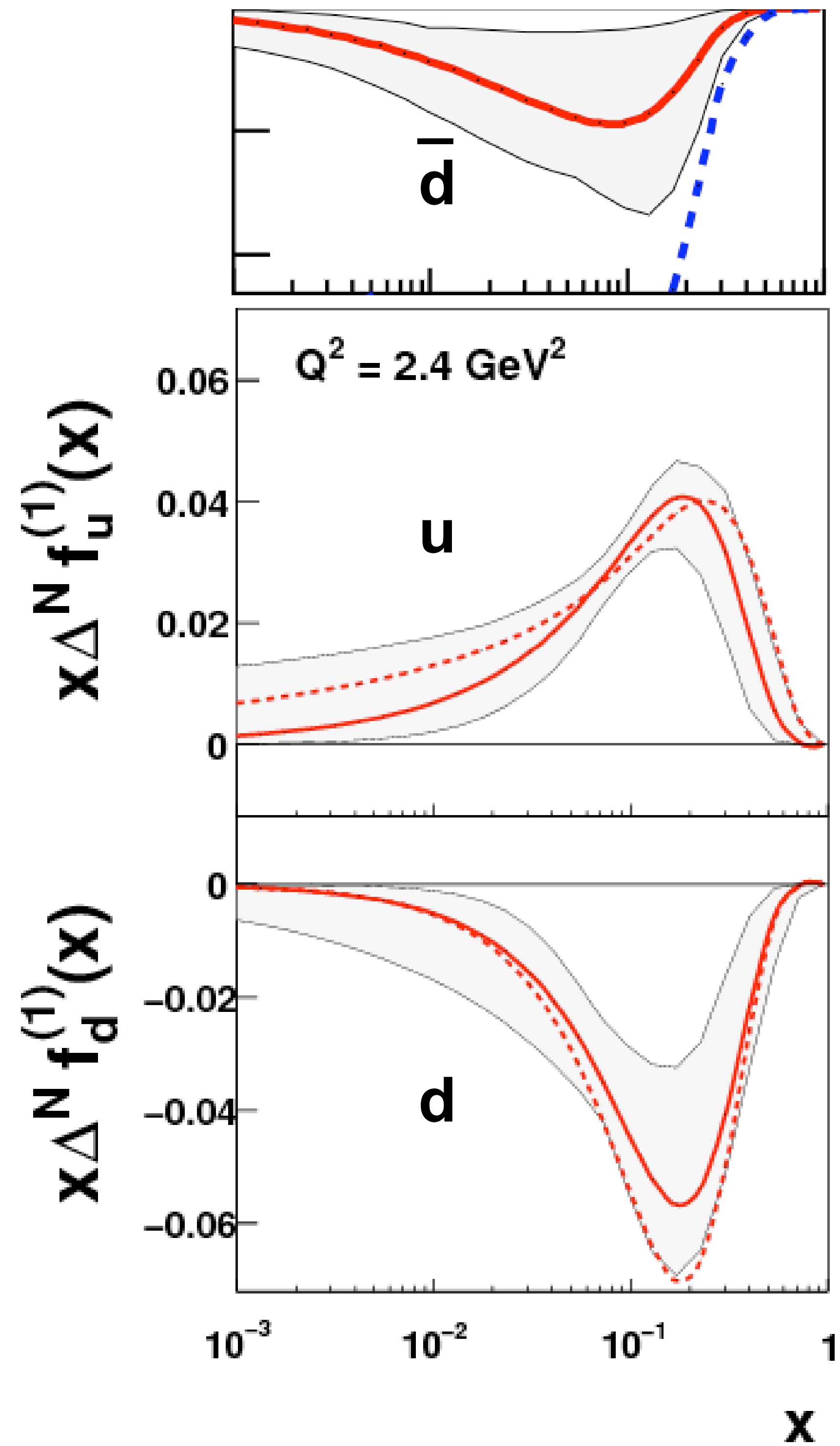
Most critical test for TMD approach to SSA

Sivers function from SIDIS

- Extract Sivers function from SIDIS

Anselmino, et.al., 2009



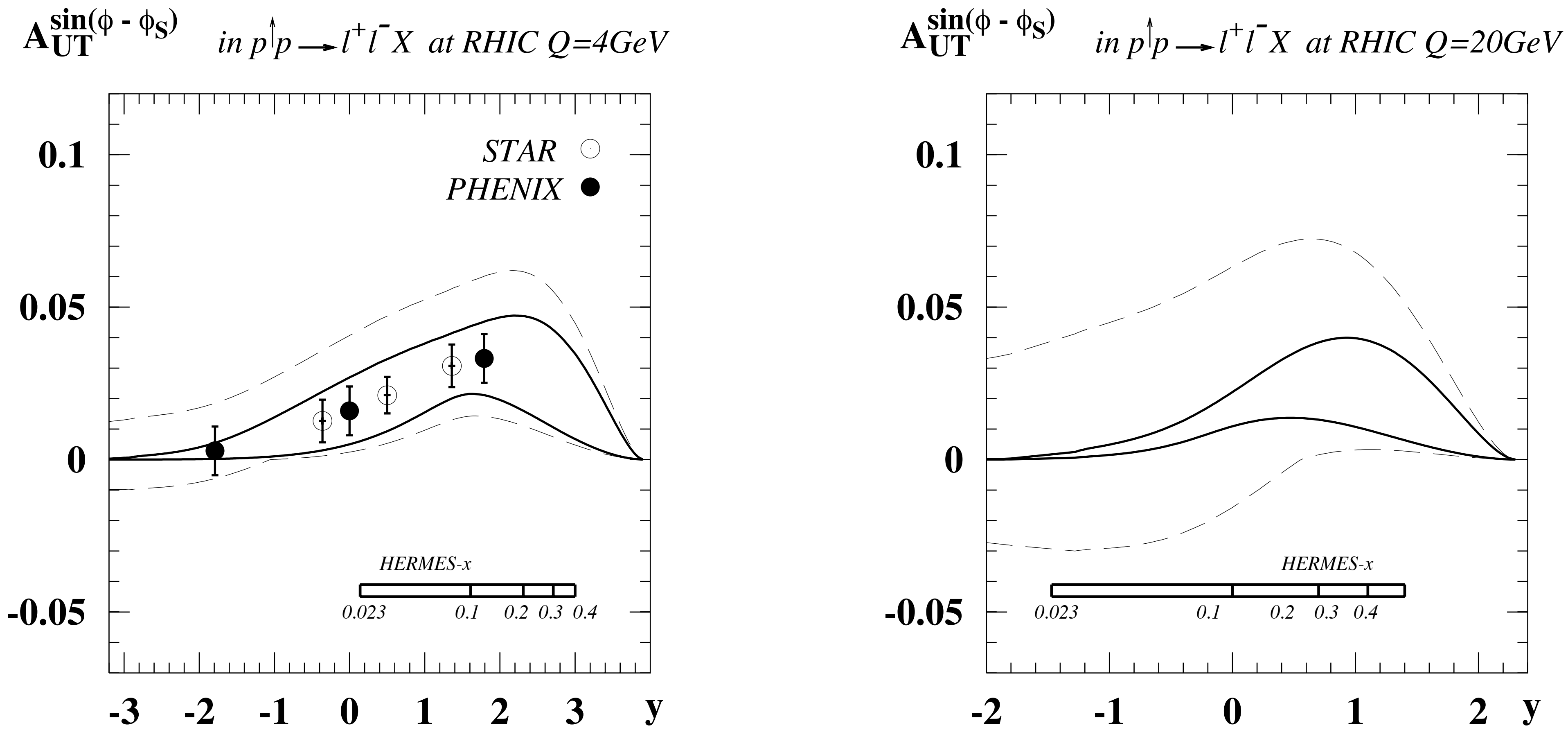


SIDIS		DY
$\mathrm{Sivers}_{u-quark} > 0$	QCD ➡	$\mathrm{Sivers}_{u-quark} < 0$
$\mathrm{Sivers}_{d-quark} < 0$		$\mathrm{Sivers}_{d-quark} > 0$

SSA for Drell-Yan dilepton production at RHIC

- Sum of Sivers functions:

Collins, Efremov, Goeke, Menzel, et.al 2006

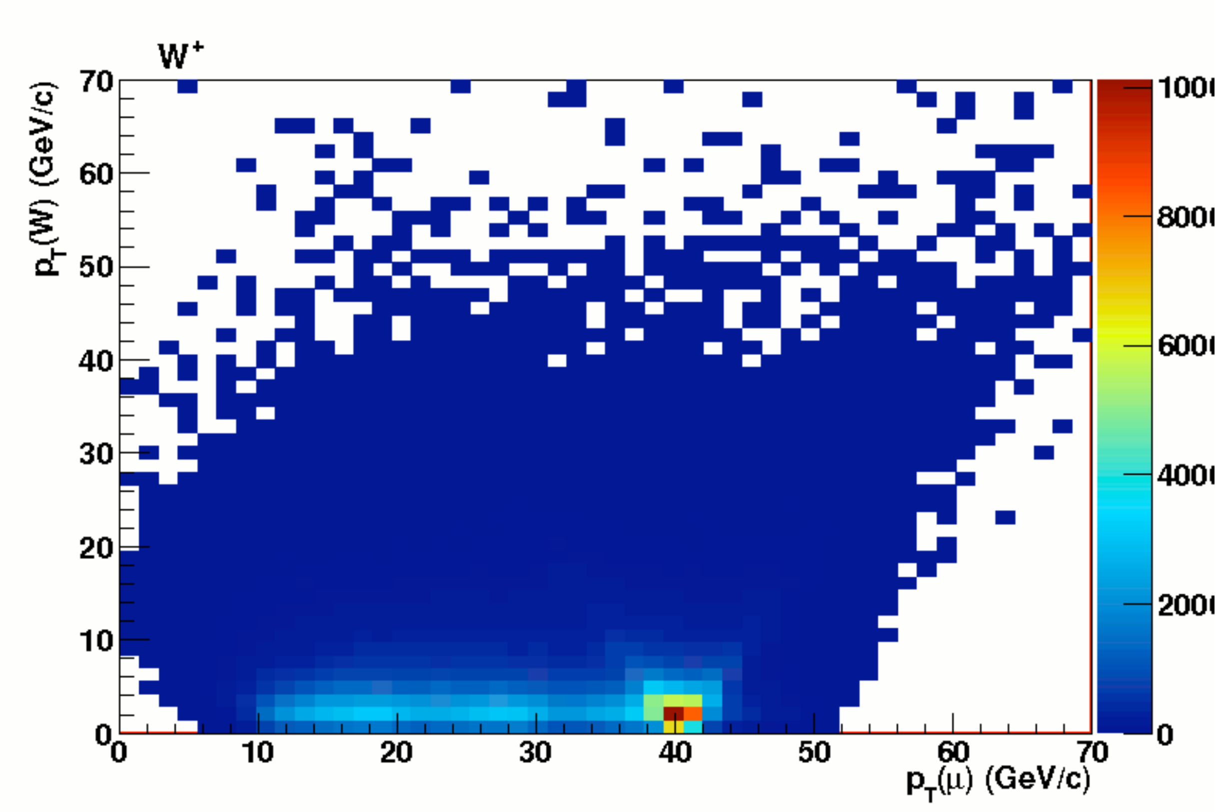


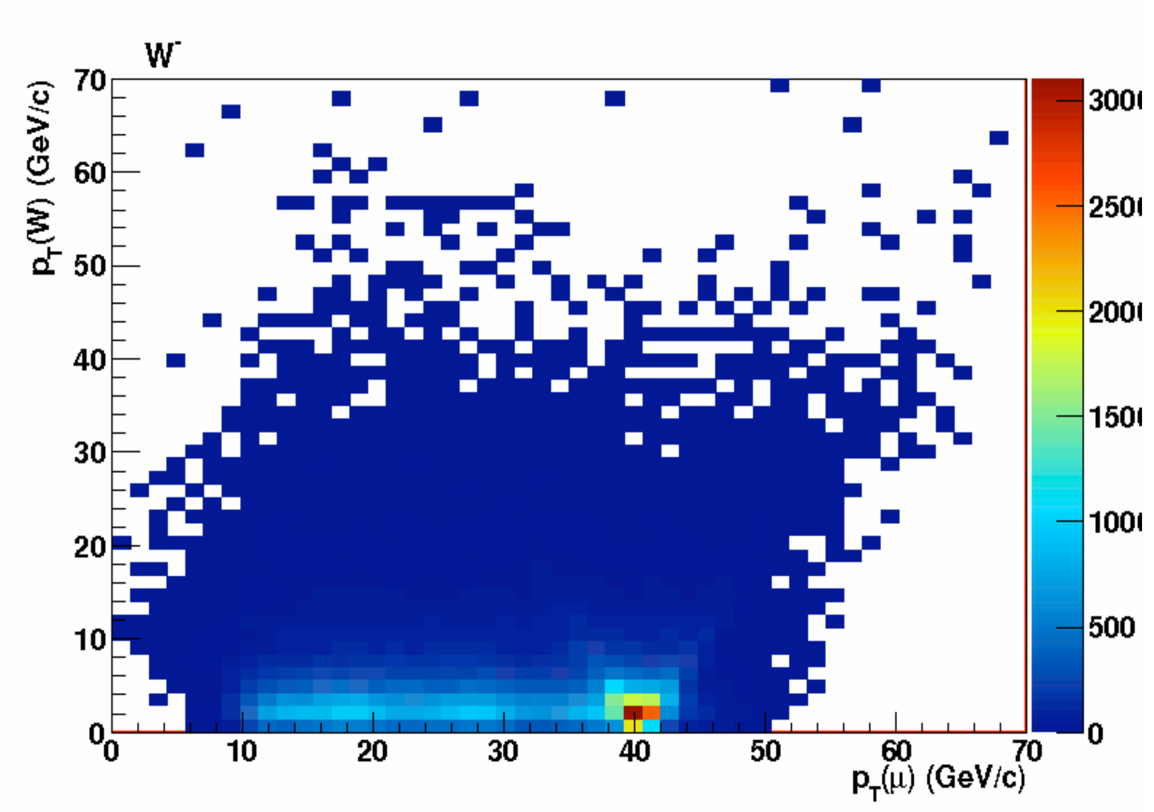
error band: 1-σ uncertainty of the fit of Sivers function

$$A_N = \frac{\sum_q e_q^2 \int \Delta^N f_{q/A^\uparrow}(x_1, \mathbf{k}_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})}{2\sum_q e_q^2 \int f_{q/A}(x_1, k_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})} \propto \frac{4}{9}\Delta^N f_u + \frac{1}{9}\Delta^N f_d$$

Production of W^+, W^- at RHIC

- W boson are primarily produced at the region: $M_W >> q_T \sim 2$GeV
  - Lepton $p_T \sim M_W/2$





Courtesy of Kempel, Lajoie (PHENIX)

- TMD approach could be used
  - W events ~ 10, 000

SSA of W boson

- Collinear factorization will have problems: Sudokov logarithm, resummation, CSS formalism
- Results in TMD approach:
  - Spin-dependent:

$$\frac{d\Delta\sigma_{A^\uparrow B\to W}(\vec{S}_\perp)}{dy_W\, d^2\mathbf{q}_\perp} = \frac{\sigma_0}{2}\sum_{a,b}|V_{ab}|^2\int d^2\mathbf{k}_{a\perp} d^2\mathbf{k}_{b\perp}\, \vec{S}_\perp\cdot(\hat{p}_A\times\hat{\mathbf{k}}_{a\perp})$$
$$\times\Delta^N f_{a/A^\uparrow}^{\rm DY}(x_a,k_{a\perp}) f_{b/B}(x_b,k_{b\perp})\,\delta^2(\mathbf{q}_\perp-\mathbf{k}_{a\perp}-\mathbf{k}_{b\perp})$$

$$x_a=\frac{M_W}{\sqrt{s}}\,e^{y_W},\quad x_b=\frac{M_W}{\sqrt{s}}\,e^{-y_W}$$

W^-: $ab=d\bar{u},\bar{u}d,\cdots$ $\quad$ W^+: $ab=u\bar{d},\bar{d}u,\cdots$

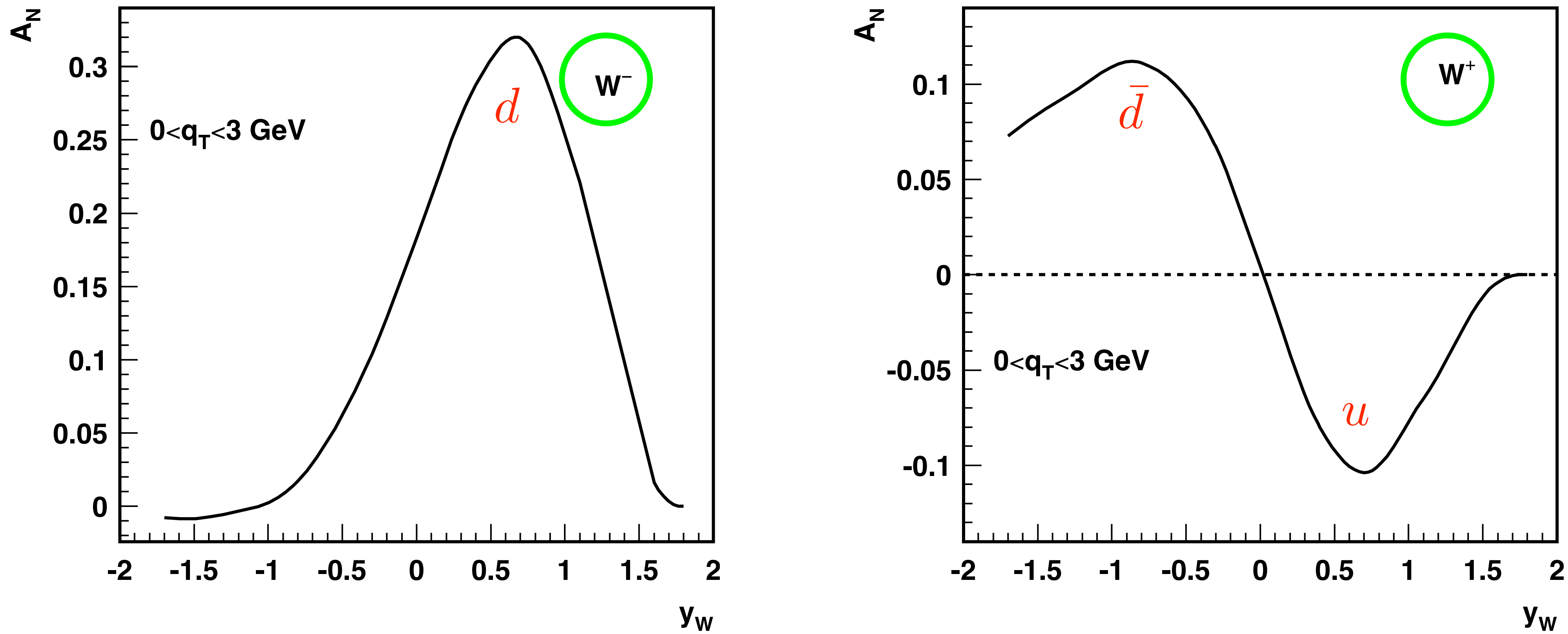
  - W- sensitive to d and u-bar Sivers function, W+ sensitive to u and d-bar Sivers function

$$A_N^{(W)} \equiv \frac{d\Delta\sigma(\vec{S}_\perp)_{A^\uparrow B\to W}}{dy_W\, d^2\mathbf{q}_\perp}\Bigg/\frac{d\sigma_{AB\to W}}{dy_W\, d^2\mathbf{q}_\perp}$$

SSA of W bosons: rapidity dependence

Brodsky, Hwang, Schmidt, 2002,
Schmidt, Soffer, 03, Kang, Qiu, 09

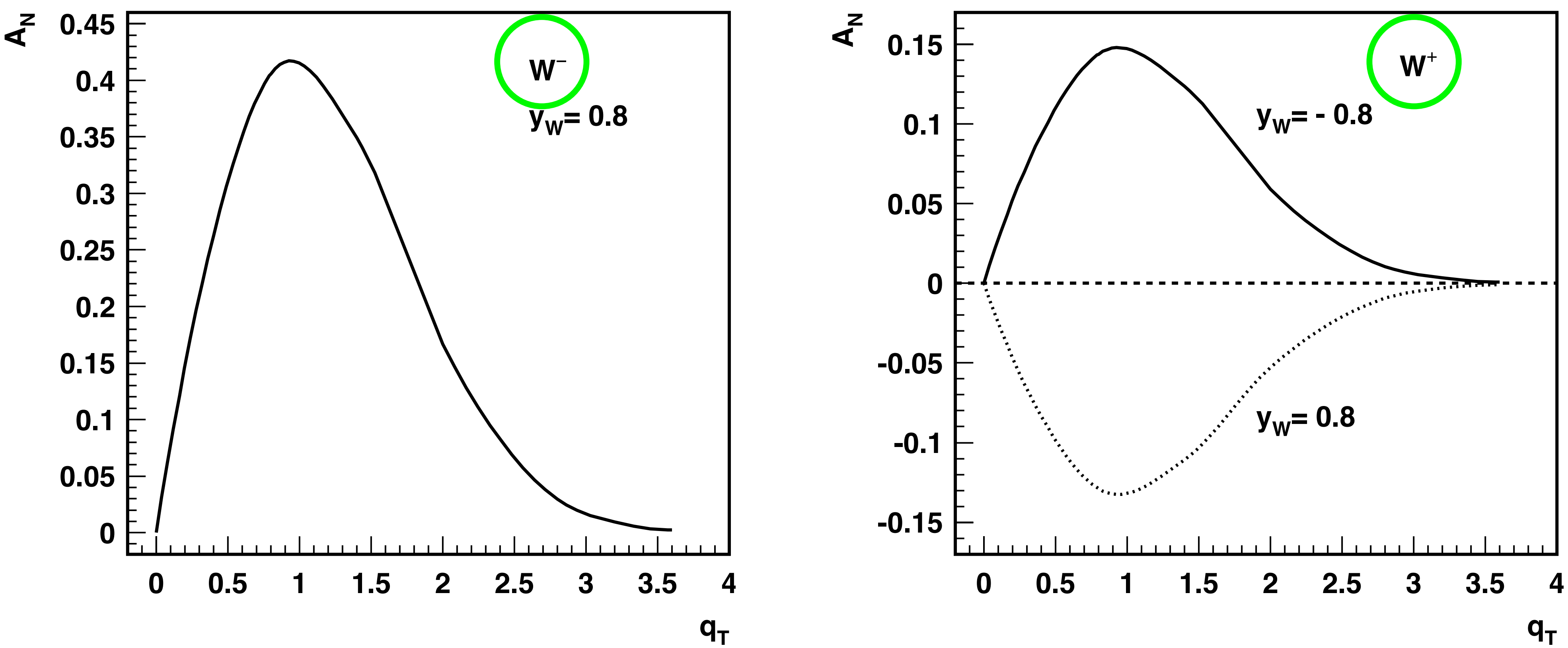
- Use the Sivers functions extracted by Anselmino et al.
- SSAs of W production at RHIC:
  - Sivers function same as DY, different from SIDIS by a sign



  - Good flavor separation

SSA of W bosons: q_T dependence

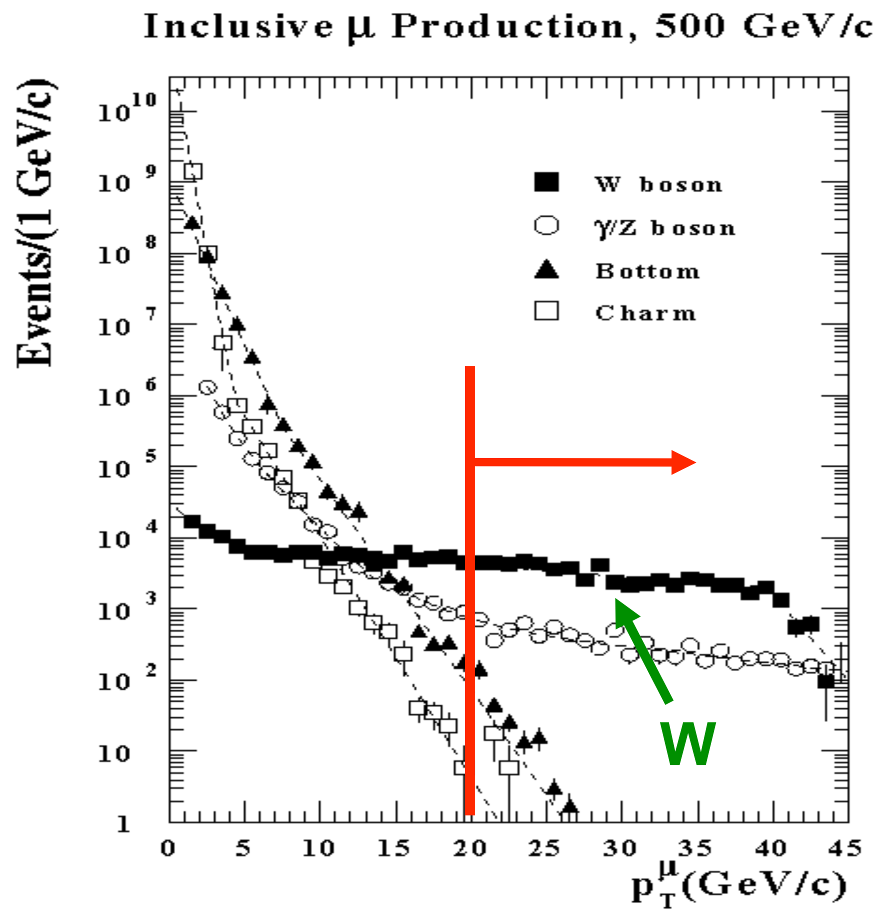
- Large asymmetry: should be able to see sign change



- But, the detectors at RHIC cannot reconstruct the W's

Lepton from W decay: W→μ ν

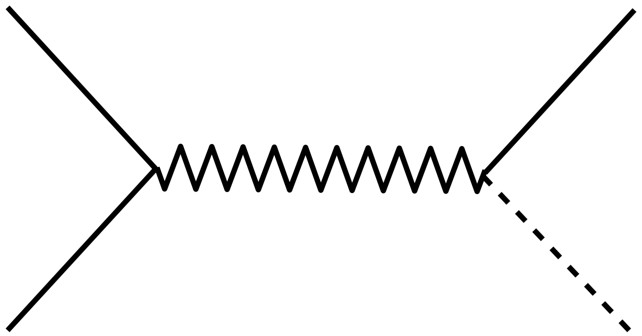
- Inclusive lepton background from Charm/Bottom dies when p_T > 20 GeV



- Idea: integrate out the neutrino to measure SSA of inclusive high p_T lepton
- However, $\sin(\Phi_S-\Phi_W)$ dependence of the SSA of W's could dilute the SSA of inclusive lepton

SSA of lepton from W decay: formula

- Spin-dependent:



$$\frac{d\Delta\sigma_{A^\uparrow B\to\ell(p)}(\vec{S}_\perp)}{dy\,d^2\mathbf{p}_\perp} = \sum_{a,b}|V_{ab}|^2\int dx_a\,d^2\mathbf{k}_{a\perp}\int dx_b\,d^2\mathbf{k}_{b\perp}\vec{S}_\perp\cdot(\hat{p}_A\times\hat{\mathbf{k}}_{a\perp})\Delta^N f^{\rm DY}_{a/A^\uparrow}(x_a,k_{a\perp})$$

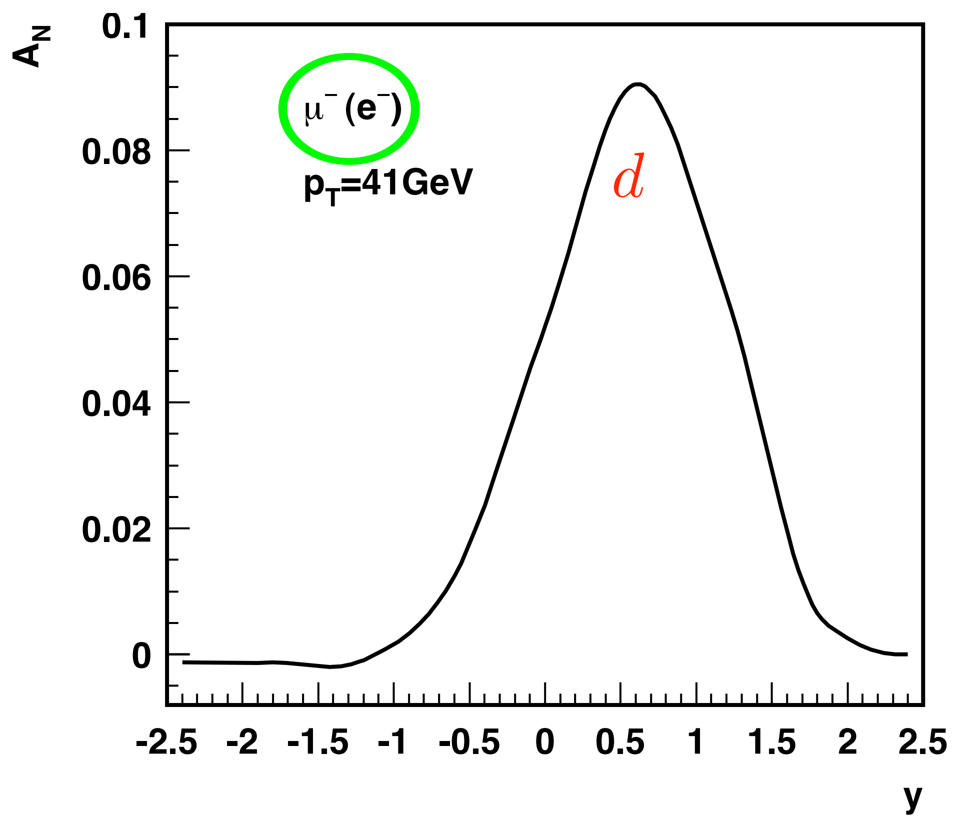
$$\times f_{b/B}(x_b,k_{b\perp})\,\frac{1}{16\pi^2\hat{s}}\,\left|\overline{\mathcal{M}}_{ab\to\ell}\right|^2\delta(\hat{s}+\hat{t}+\hat{u})$$

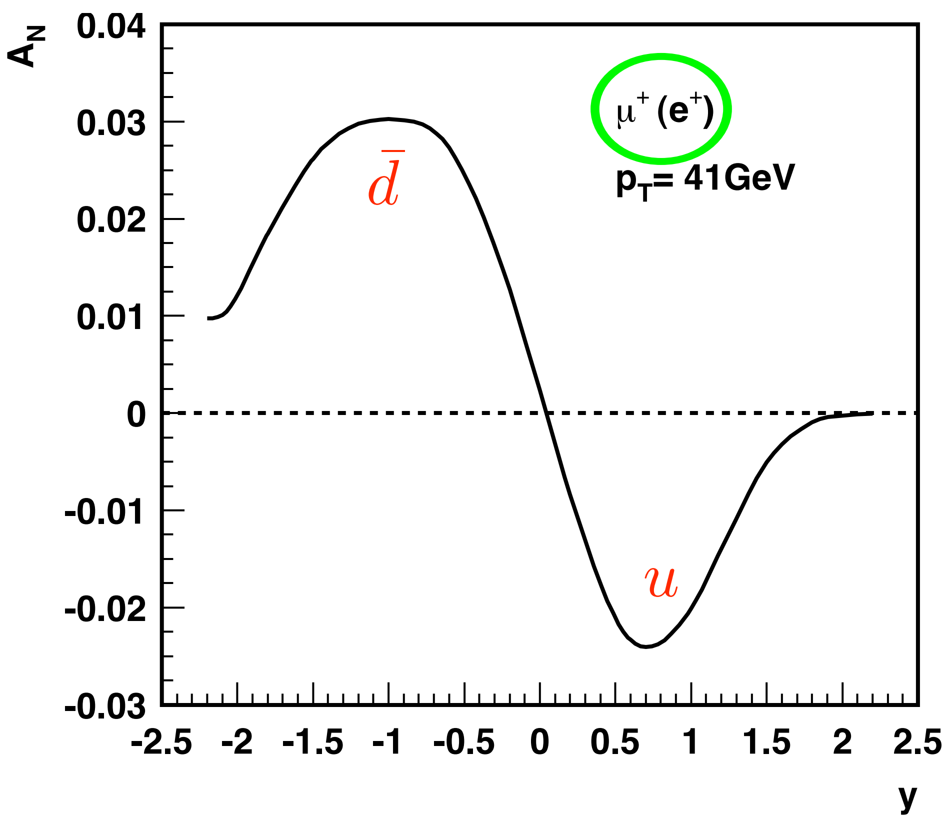
$$\left|\overline{\mathcal{M}}_{ab\to\ell}\right|^2 = \frac{8({\rm G}_F M_W^2)^2}{3}\frac{\hat{t}^2}{(\hat{s}-M_W^2)^2+M_W^2\,\Gamma_W^2} \qquad ab=\bar{u}d,\bar{u}s,u\bar{d},u\bar{s}$$

$$\left|\overline{\mathcal{M}}_{ab\to\ell}\right|^2 = \frac{8({\rm G}_F M_W^2)^2}{3}\frac{\hat{u}^2}{(\hat{s}-M_W^2)^2+M_W^2\,\Gamma_W^2} \qquad ab=d\bar{u},s\bar{u},\bar{d}u,\bar{s}u$$

SSA of lepton from W decay: rapidity dependence

- SSA of inclusive lepton is still sufficient for measurement:

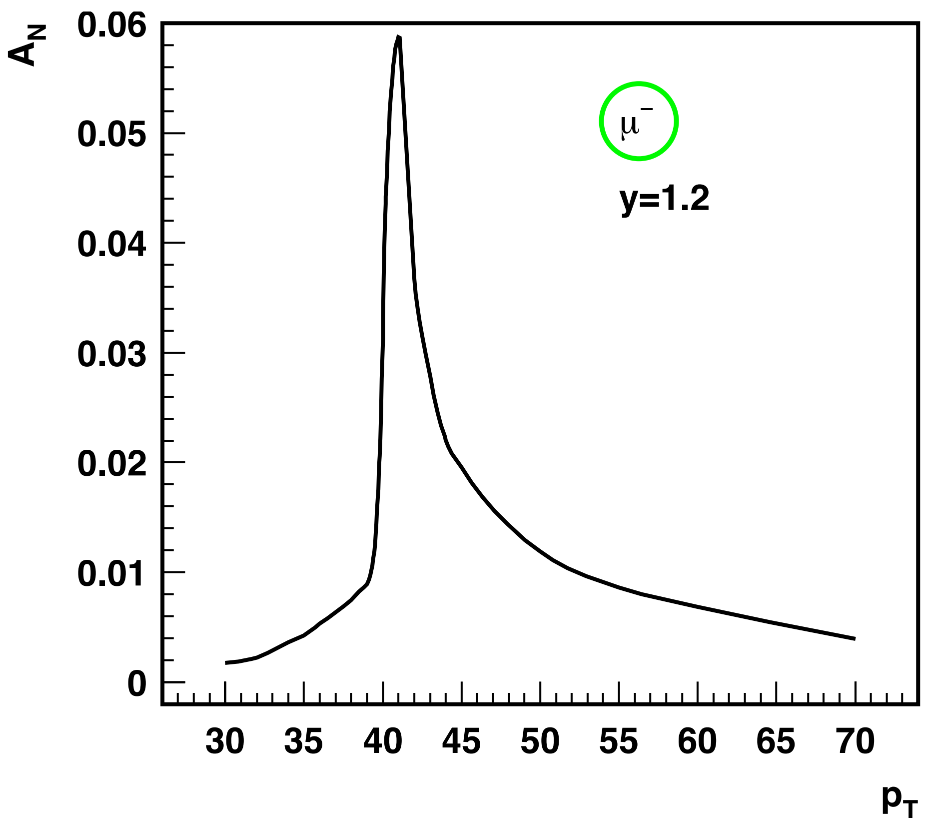


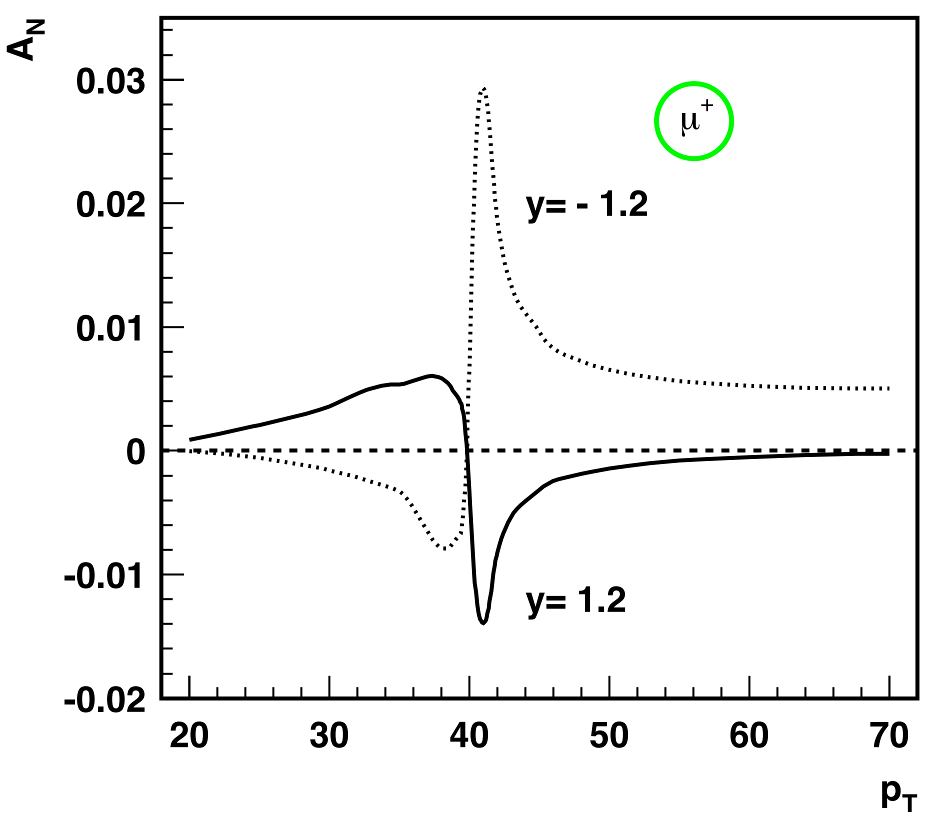


- Good flavor separation:
  - $\mu^-(e^-)$ at central-forward rapidity is sensitive to d Sivers function
  - $\mu+(e^+)$ at forward is sensitive to u Sivers function, at backward is sensitive to d-bar Sivers function

SSA of lepton from W decay: p_T dependence

- p_T behavior of SSA of leptons:

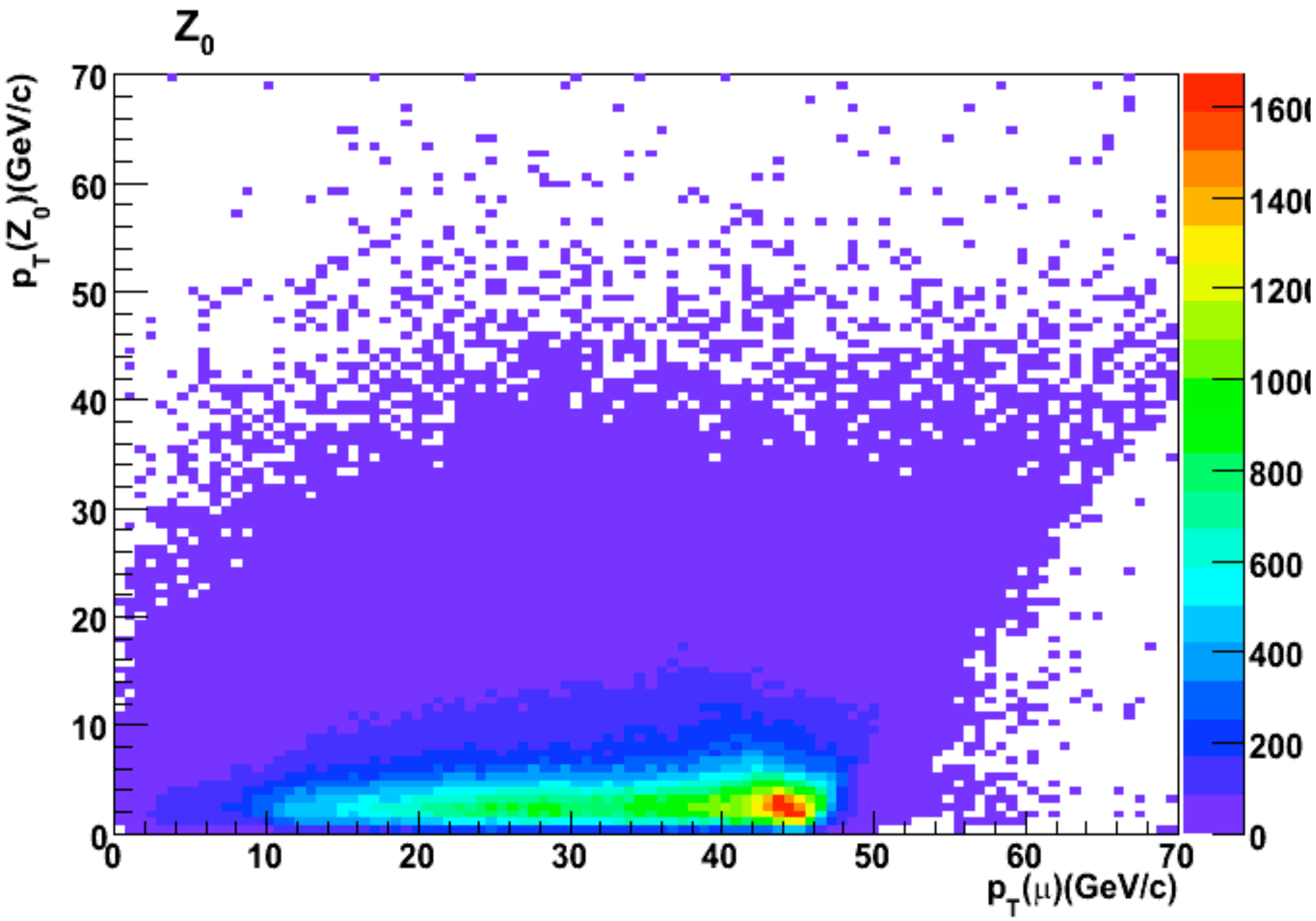




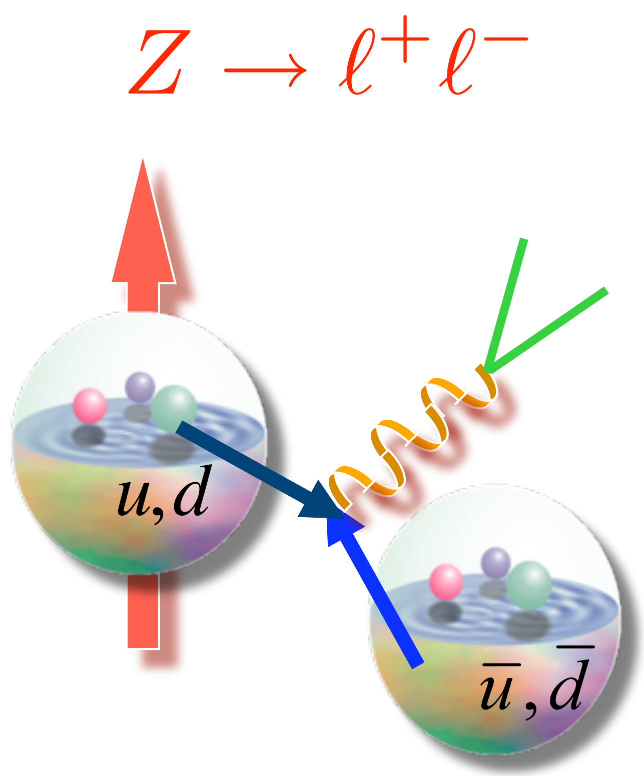
- inherit the key features of W asymmtry
- sharply peeked around $p_T \sim M_W/2$, should help control the potential background

What about Z boson?

- RHIC can reconstruct Z boson



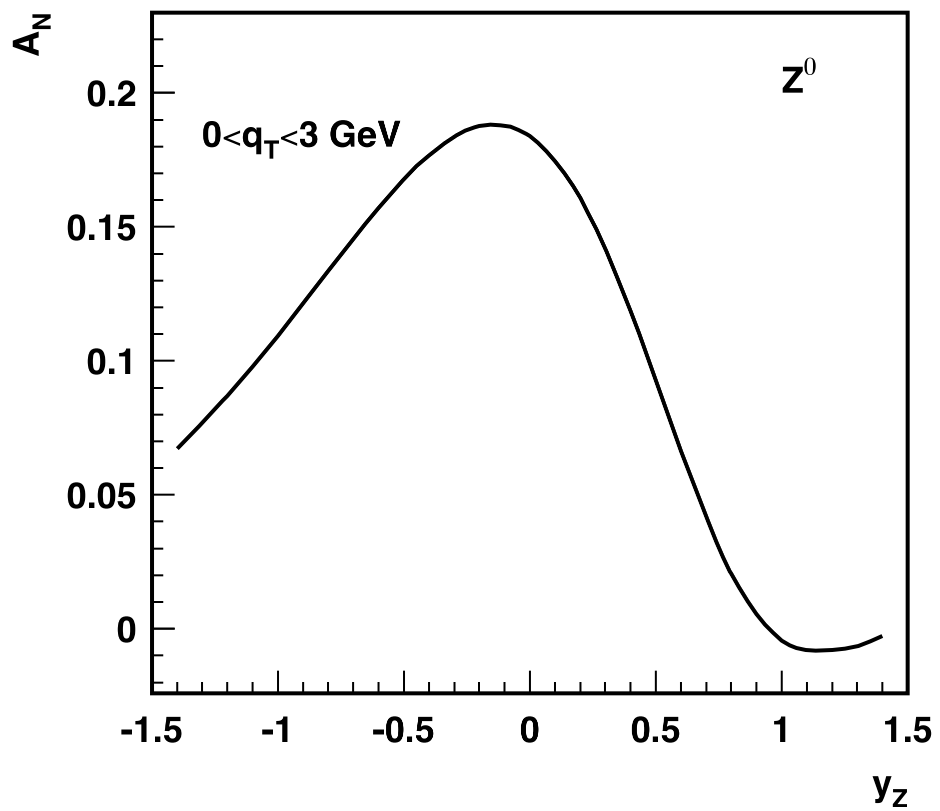
Courtesy of Kempel, Lajoie (PHENIX)

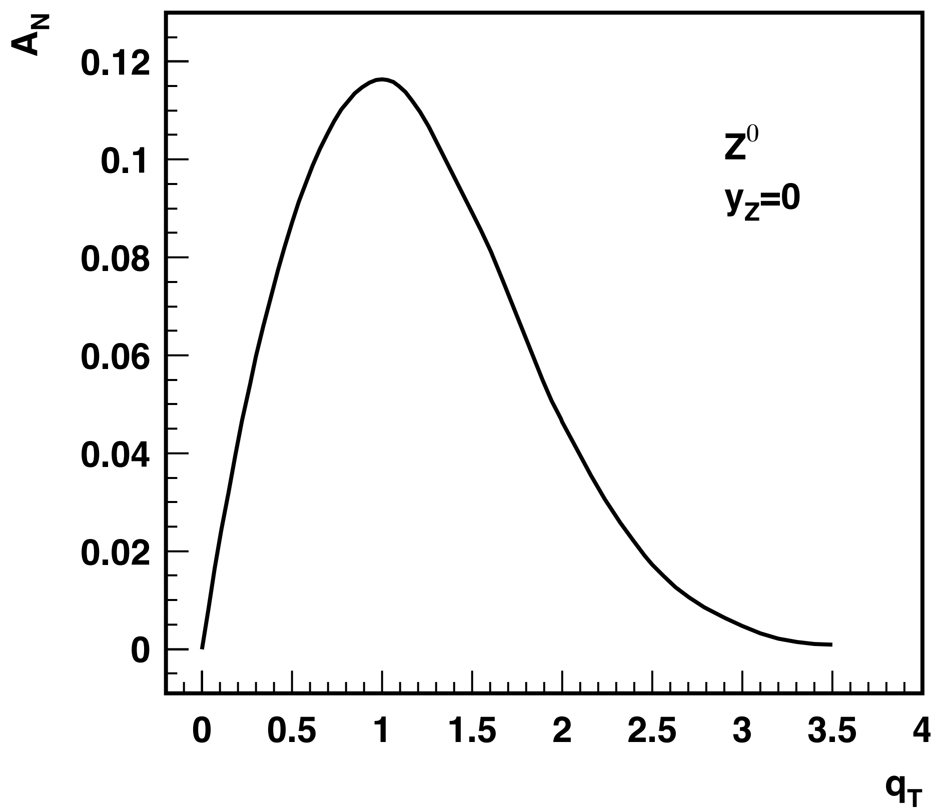


- Events down by an order of magnitude compared to W boson:
  - ~1000

SSA of Z boson at RHIC

- Prediction for RHIC kinematics:





- Fairly large asymmetry, should be very good channel to test sign change if one can accumulate enough Z boson

Summary

- Sign change of Sivers function between DY and SIDIS is the most critical test for our current understanding of SSAs
- Besides the standard DY dilepton production, we propose to use the SSAs of W and/or Z boson production to test this sign change
- Lepton decayed from W^+, W^- boson could give good flavor separation, give even separate tests for Sivers function of different flavors
- Z boson might also be a good channel if one could accumulate enough events

Thank you!